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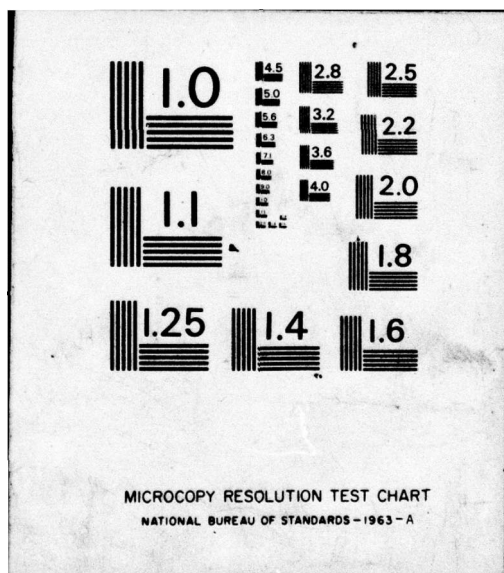
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DEPARTMENT OF THE NAVY
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METHOD AND SOME RESULTS OF ADAPTIVE MEASUREMENTS

[Kolesnikov, A. G., A. N. Paramonov, and V. M. Kushnir, Metodika i nekotoryye rezul'taty adaptivnykh izmereniy, Morskoy Gidrofizicheskiy Institut, Trudy, No. 6 (56), 1971, pp. 95-108; Russian]

The article presents the principles of investigation of physical fields in the ocean with adaptation of the measuring algorithm to the statistical structure of a field and describes the results of experiments.

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An important condition for obtaining reliable scientific data on the physical processes in the seas and oceans is the matching of the parameters of the meters and the method of their application with the statistical structure of the hydrophysical fields being studied. As the matching criterion, use may be made in the general case of the relationship, predetermined with a definite degree of probability, between the frequency band of the meter Δf_y and the "spectral window" Δf_n , in which practically the entire fluctuation energy of the investigated element of the hydrophysical field is concentrated.

The traditional methods of research in the sea and modern technical devices used in oceanography do not at the present time permit the achievement of the required statistical agreement between the measurements and the field under study. In most cases, the algorithms of measurements conducted in the sea remain unchanged during the period of observation and as a rule, the instruments operate with a fixed speed of response that is independent of the structure of the process. In sounding or towing, the speed of the relative motion of the sensor and medium is also maintained constant irrespective of the dependence on the configuration and variability of the field element being measured. This method of investigation has significant drawbacks, since, as is well known,¹⁻⁴ distortions of measurement results and processing of primary data depend not only on the characteristics of the meter and measuring conditions (dimensions of the sensors, their orientation and motion in the medium studied, method of converting the signal to digital form and frequency of conversions, duration of the recording, etc.), which during the observation remain unchanged and are known in advance, but also on the structure of the investigated process itself. Since the statistics of the field element studied (and hence, Δf_n) are unknown during the measurement, and a second experiment under identical "sea conditions is impossible, there is always the following alternative:

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$$\Delta f_y > \Delta f_n; \quad \Delta f_y < \Delta f_n.$$

The first inequality signifies that the meter gives excess data, and in addition, because of the limitations of a series of observations during the analysis, restricts the scale to the range of low frequencies. Figure 1 a shows a spectrum of transparency fluctuations, the frequency of whose measurements considerably exceeded Δf_n . The "spectral window" was "not filled" in this case. The fluctuation spectrum ⁿ shows a spike in the range of lowest frequencies f_0 , after which the spectral intensity retains a low constant value determined by the meter noise.

*Numbers in the right margin indicate pagination in the original text.

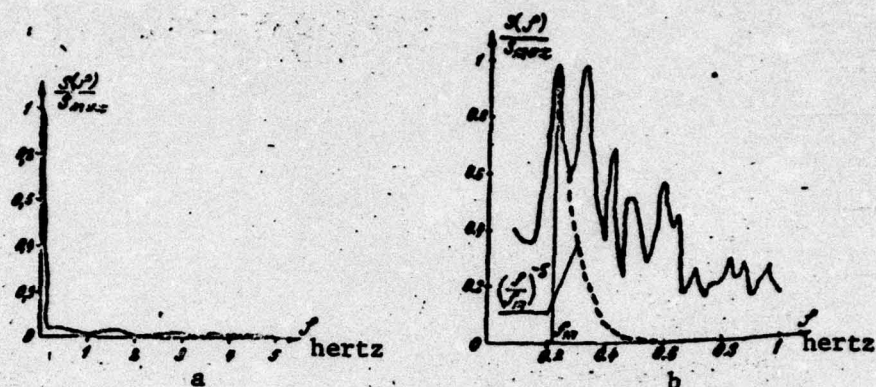


Figure 1. a) Spectrum of seawater transparency fluctuations, bounded in the low-frequency range; b) Spectrum of fluctuations of sea surface elevation, measured with large distortions.

When $\Delta f_y < \Delta f_n$ (the frequency band of the physical process is greater than that of the meter), the results of the study are distorted by the suppression or transformation of the high-frequency components of the process. An example of this is the fluctuation spectrum of elevations of the sea surface (Fig. 1 b), obtained by analyzing the data of measurements whose frequency was smaller than f_n . In the same plot, the dashed curve shows the dependence $\frac{S(f)}{S(f)_{\max}} = \left(\frac{f}{f_{\max}}\right)^{-5}$, which corresponds to the Phillips spectrum for wind waves. As is evident from the figure, the fluctuation spectrum is highly distorted and does not permit a correct interpretation of the result of the measurements. /97

Numerous studies have shown that the statistical structure of most real hydrophysical fields is variable in time and space. The unsteadiness of physical fields in the ocean is related to seasonal, diurnal, tidal, and other oscillations. In some cases, an intermittent turbulence is observed, when periods of low intensity of the fluctuations alternate with periods of their appreciable increase.⁵ In all these cases, the value of Δf_n changes.

The lack of sufficiently complete a priori information and the unsteadiness of the physical process do not permit one to determine in advance the conditions of measurement and characteristics of the meters, or to correct the results of the measurements. Therefore, in order to limit the errors of measurement and processing to a predetermined level and obtain reliable information, it is necessary to change the algorithm of the measurements automatically during the studies.

Studies characterized by a rearrangement of the measurement algorithm and its "fitting" to the statistical structure of the investigated field for the purpose of obtaining an acceptable and constant level of distortion of the results or limiting the lower frequencies are called adaptive, and the measuring devices or systems which perform this rearrangement in the real time of the measurements are called adaptive meters or systems.

The fundamental principles of operation of adaptive meters are: analysis of the measured signal in real time to find the statistical element making the chief

contribution to the error of measurement and processing; comparison of this parameter with a given criterion of accuracy and, depending on the result of the comparison, appropriate modification of the measurement algorithm.

Analysis of the distortions of a random field by real meters shows^{6,7} that the chief contribution to the measurement errors is made by small-scale components corresponding to the Nyquist frequency, or, in other words, field components whose scale is comparable to or smaller than the minimum scale characteristic of a specific meter. Therefore, to check the distortion level in real time, it is sufficient to have information on the behavior of the spectrum of the investigated process in the high-frequency region, bounded from above by the minimum scale of the meter itself. The statistical parameter characterizing the behavior of the high-frequency region of the spectrum is determined by the asymptotic expansion of the integral Fourier transform of the correlated function $R(\tau) = \sigma_x^2 \rho(\tau)$ of this process:⁸

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$$\frac{s(\omega)}{2\sigma_x^2} = \int_0^\infty \rho(\tau) e^{-j\omega\tau} d\tau = Re \left[\sum_{n=0}^{N-1} \frac{\rho_0^{(n)}}{(j\omega)^{n+1}} + O\left(\frac{j}{\omega N}\right) \right] \dots, \quad (1)$$

where $s(\omega)$ is the spectrum of the process: $\rho_0^{(n)}$ is the n th derivative of the correlation coefficient when $\tau \rightarrow 0$; σ_x^2 is the variance.

The range of characteristic dimensions of hydrophysical meters is bounded from below by values on the order of fractions of a millimeter and hundredths of a second, and from above, by several meters and seconds. These dimensions correspond to portions of the spectrum of ocean turbulence located in the region of universal equilibrium, where there is no energy input to the fluctuations, and the spectra are characterized by a continuous decrease and are structurally similar to Markov spectra.⁹ A transformation of Eq. (1) for such processes gives the following expression for the high-frequency portion of the spectrum $s_v(\omega)$:

$$s_v(\omega) = \frac{D(\Delta)}{T_k \omega^2},$$

where $D(\Delta)$ is the dispersion of increments of the measured process during the minimum interval between the measurements T_k .

A formal analysis of the errors of reconstruction of the initial observation from discrete readings and of the errors of low-frequency filtering, calculation of the spectrum and conversion of the signal to digital form by various digital-analog converters shows that there exists a linear or quasi-linear relationship between the dispersion of these errors and $D(\Delta)$.^{10,11,12} The coefficients of proportionality between them depend on the method of discretization, modulus of the frequency characteristic of the sensor, time between measurements, and other parameters known in the course of the experiment.

Thus, the dispersion of increments during the minimum possible interval between measurements $D(\Delta)$ is a statistical element determining the behavior of the high-frequency region of the spectrum and hence, the measurement and data processing errors.

The dispersion of the increments can be obtained with a given probability in the real time of observations, this being a necessary condition for fitting the meter to the structure of the field studied. /99

Analysis shows that in order to determine the algorithm of adaptive measurements, it is more convenient to use, not the sample estimate of $D(\Delta)$, but the mean modulus of increments $M(|\Delta|)$ related to this estimate. This relationship for non-Gaussian random processes has the following form:

$$N(|\Delta|) = \sqrt{\frac{2}{\pi}} D(\Delta) \left(1 - \frac{\gamma_x}{2}\right) = \sqrt{\frac{2}{\pi}} D(\Delta) \left(1 - \frac{\gamma_x}{2}\right),$$

where $\gamma_\Delta = \frac{\gamma_x}{2}$ is the excess coefficient of increments Δ of a random process $x(t)$ having an excess coefficient γ_x . The rate of convergence of the sample quantity

$|\Delta|_n$ to its general value $|\Delta|_n = \frac{1}{n} \sum_{i=1}^n |\Delta_i| = N(|\Delta|)$ is approximately twice as high

as the analogous convergence rate of the sample increment dispersion, and is determined from a Cheyshev inequality, which after transformations is written as

$$1 - \sqrt{\frac{0.5x-1}{n\rho}} \leq \frac{|\Delta|_n}{N(|\Delta|)} \leq 1 + \sqrt{\frac{0.5x-1}{n\rho}}, \quad (2)$$

where $|\Delta|_n$ is the sample value of $M(|\Delta|)$ at n points; $1 - p$ is the estimation probability of $M(|\Delta|)$. Replacement of the calculation of increment dispersion by the mean modulus of increments in real time appreciably simplifies the technical application of the adaptive principle of measurement and makes it possible to reduce the time of signal analysis.

It follows from expression (2) that for a 20% spread of the sample values relative to the true value (a spread of this magnitude or larger takes place in the study of the statistical structure of physical fields in the ocean¹³), averaging can be performed over 63 measurements with a probability of 0.8. The notation of the algorithm for calculating the estimate of the asymptotic element of the small-scale fluctuation component model, for which the mean modulus of increments is used, is as follows:

$$|\Delta|_{np} = \frac{1}{m} \sum_{i=1}^m (x_{i,p} - x_{i,p+1}),$$

where m is the scale factor and n is the averaging step. For five types of commonly used digital computers, the duration T_v of the computations and volume of the storage device P_v were determined for the same measuring channel. The results of the calculations are given in the table.

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Table

| Parameter | Type of computer | | | |
|-------------------------------------------|------------------|---------|-------|--------|
| | Minsk-22 | Dnepr-1 | M-220 | BESM-4 |
| Duration of calculations, μsec | 1460 | 666 | 520 | 802 |
| Volume of SD for calculations, cells | 68 | 68 | 68 | 68 |
| Total volume of SD | 8192 | 1536 | 4096 | 4096 |

If the number of measuring channels is n_v , and the maximum frequency of measurements in each channel is f_v , the boundary relations for the computer capabilities may be written as follows: $\frac{1}{T_v} \geq n_v f_v$, $P_{comp} \geq n_v P_v$, where P_{comp} is the volume of the storage cell of a given computer type.

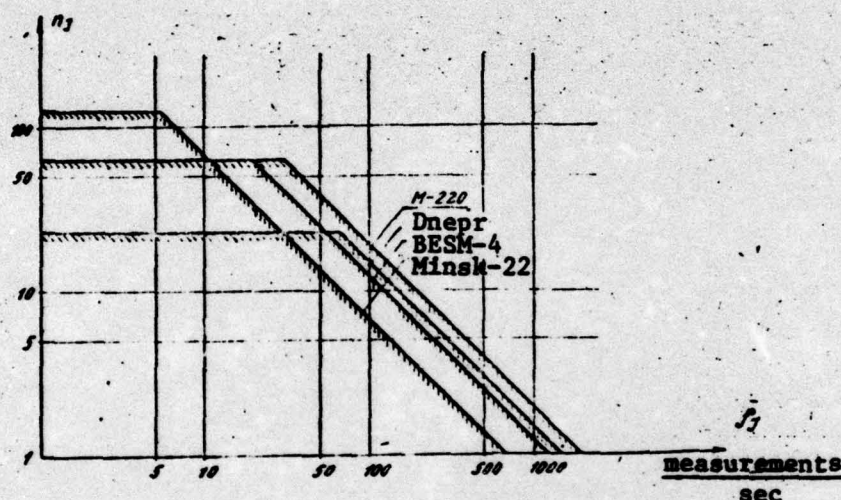


Figure 2. Region of possible use of different types of digital computers for calculating in real time the asymptotic element of the model of the small-scale component of fluctuation processes.

On the basis of the above relations, Fig. 2 shows the regions of possible application of different computer types as calculators of a multichannel adaptive measuring system. The plots show that for a complete loading of the computer at a maximum measuring frequency of 20 times/sec in each channel, the limiting number of channels for different computers ranges from 22 to 32. This indicates that universal-type computers should be used only for adaptive control of meters integrated in a single automated system and operating simultaneously. For individual meters in which the number of channels is no greater than 10, these types of calculators will not be used effectively. In this case, it is preferable to entrust the calculation of the asymptotic element of the small-scale component model of a hydrophysical process to a specialized calculator connected to the feedback circuit of the measuring unit of the equipment.

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On the basis of the above principles, the Marine Hydrophysical Institute of the Ukrainian Academy of Sciences has designed a measuring unit of the equipment for adaptive studies of physical processes in the sea. This unit was tested on an experimental sea range. The general block diagram of the set is given in Fig. 3. The equipment includes: a set of sensors of hydrophysical characteristics (D_1, D_2, \dots, D_n), a multichannel dc amplifier unit (A), and device for receiving, controlling the recording and coding information (CU), a 15-track tape recorder (TR), a set of electronic analog recorders ($ER_1 - ER_3$), a digital printer (DG), an electric puncher (EP), and an adaptive control device (AD).

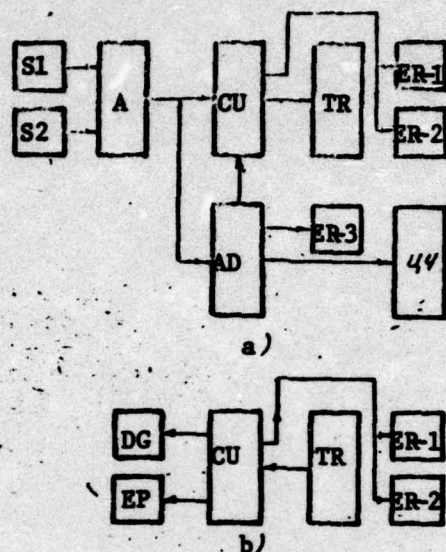


Figure 3. Block diagram of measuring unit for adaptive measurements: a) under measuring conditions; b) under reproduction conditions.

The newly designed equipment was used to measure the elevation of the sea surface, wind pressure on the wave, horizontal components of the flow velocity on several levels, and fluctuations of the index of attenuated directed light and temperature. The unit was designed for synchronous operation on 8 analog and 8 digital measuring channels, with a measuring frequency of 25 Hz in each channel. The recording equipment can operate in the cyclic or slave mode. The hydrophysical parameter sensors were installed on a stationary gradient mast rigidly mounted on a concrete support at a depth of 15 m and a distance of 300 m from the shore.¹⁴ The measuring signals from the sensor outputs were transmitted to a shore laboratory over a multicore cable, and after passing through a multichannel amplifier, reached the inputs of a control unit (CU) and an adaptive control device (AD). The latter included an analog-code converter, a memory register, a computer, and a system for automatic control of the measurements.

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The output signal of the amplifier is converted to the digital form $Y(iT_k)$ with period T_k between readings. The digital data are fed to the computer, where the sample value of the mean modulus of increments between neighboring numbers is determined in real time from the given averaging step. The result of the calculations of $|\bar{\Delta}|_n = \frac{1}{n} \sum_{i=1}^n [Y_i - Y_{i+1}]$, whose magnitude is determined by the structure

of the physical process being measured, enters the input of an automatic control system, where it is compared with a preassigned value of the mean modulus of increments $M(T_k)$, which is related to the allowed distortion level of the auto- and mutual spectra characterizing the process studied. Depending on the sign and magnitude of the difference of $M(T_k)$ and $|\bar{\Delta}|_n$, a signal acting on the measurement algorithm is formed at the output of the system. In the elaborated unit, this signal controls the oscillator frequency synchronizing the operation of the analog-code converter and channel commutator of the control unit, and thereby performs the adaptive matching of the passband of the meter with the "spectral window" of the process studied.

The value of the measurement frequency is recorded in analog form with an electronic plotter and in digital form with an electronic counting frequency meter. The output voltage from the comparison unit of the control system may be used to control the measurements in other channels, for example, the rate of immersion of a towed or sounding device, orientation of the sensor in the flow, dimensions of the measuring base of the instrument or system of sensors, etc.

The basic condition for carrying out studies by means of an adaptive measuring unit was to maintain at a given level the relative magnitude of distortions (q) of the power spectrum of fluctuation processes in the surface layer of the sea, irrespective of the frequency distribution of energy

$$q = \frac{s_{\max}}{P_{\Omega}},$$

where s_{\max} is the maximum value of the spectrum and P_{Ω} is the absolute distortion level.

The quantity q determines the decrease of the spectrum into the region of small-scale processes and may be given by taking into account the minimum scale of the fluctuations accessible for study. The scale is determined by the structural and metrological characteristics of the meters.

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The analysis performed showed that the reciprocal of the relative error of spectral distortions is related to the dispersion of increments during the minimum time between measurements, to the power exponent of the spectral decrease, to the increase in frequency and to the dispersion of fluctuations or their dynamic range \mathcal{L}_{ϕ} , and is expressed by the following relation:

$$\frac{1}{q} = \left[\frac{\sigma_x^2}{D(\Delta)} \right]^{\frac{s}{s-1}} \left[\frac{x^{(s-1)(n_s+1)}}{(s+n_s)} \frac{\sum_{j=1}^{\infty} \frac{1}{(j+q,s)^s} + \frac{1}{(j-q,s)^s}}{\sum_{j=1}^{\infty} \frac{1}{(j+q,s)^2} + \frac{1}{(j-q,s)^2}} \right]^{\frac{s}{s-1}},$$

where σ_x^2 is the variance of fluctuations of the process studied; n_s , s are the power exponents of the increasing and decreasing branches of the spectrum, respectively; $D(\Delta)$ is the dispersion of the signal increments.

Since the end result of the studies was the determination of the spectral characteristics of the processes, it was convenient to assign the distortion level in terms of the number of orders P_q by which the spectrum decreases from the maximum to the minimum value. From the latter expression it is easy to obtain $P_q = -\log q$.

$$P_q \approx \frac{s}{s-1} \log \frac{\sigma_x^2}{D(\Delta)} + A_q, \quad \text{where } A_q = 1.95-2.$$

Since the dispersion of increments $D(\Delta)$ is uniquely related to the mean modulus of increments $M(|\Delta|)$, and on the basis of the Chebyshev inequality the fluctuation dispersion is expressed with reliable probability $(1 - P)$ in terms of the magnitude of the dynamic range $\mathcal{L}_{\phi} < \frac{2\sigma_x}{\sqrt{P}}$, the above relation may be written as follows:

$$P_2 \approx \frac{2s}{s-1} \lg \frac{I_\varphi}{|\Delta|} + \frac{2s}{s-1} \lg \frac{1}{x\sqrt{\rho}} + P_2.$$

For physical processes in ocean-atmosphere boundary layers, the exponent s of the spectral decrease lies within the range of 4-5, so that the preceding expression for $(1 - P) = 0.8$ may be reduced to the following simple form:

$$|\Delta| \approx 0,55 I_\varphi \cdot 10^{-0,57 P_2} = M(T_k). \quad (3)$$

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For physical processes structurally similar to a locally isotropic turbulence ($s = 2$), the relation for the mean modulus of increments is

$$|\Delta| = 0,55 I_\varphi \cdot 10^{-0,3 P_2} = M(T_k). \quad (4)$$

For a given P_q and hence $M(T_k)$, the adaptive meter calculates in real time the mean modulus of increments $|\Delta|$, compares it with $M(T_k)$, and automatically finds the measurement frequency required, maintaining it at a constant level, if the measured physical process has properties similar to those of a stationary one.

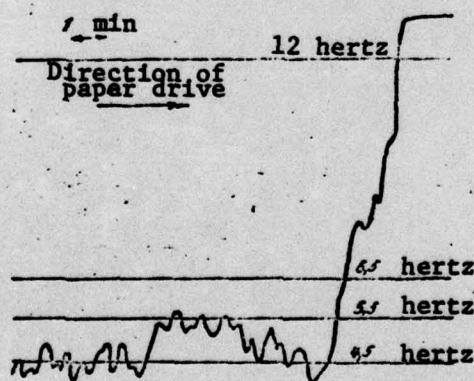


Figure 4. Typical trajectory of adaptive scanning of measurement frequency.

Figure 4 shows a typical scanning trace of the measurements with an adaptive meter. Initially, when the feedback circuit was disconnected, the measurement frequency was maximum and equal to 15 Hz. At the instant when the feedback was connected, the measurement frequency decreased to a certain level that was subsequently kept constant with only slight fluctuations if the process was stationary.

Figure 5 shows elevation spectra of the sea surface obtained with an adaptive meter under various hydrometeorological conditions and a given value $P_q = 3$. In this figure, the spectra were plotted in normalized form: $i_m = 2m \frac{f}{f_k}$ is laid off along the

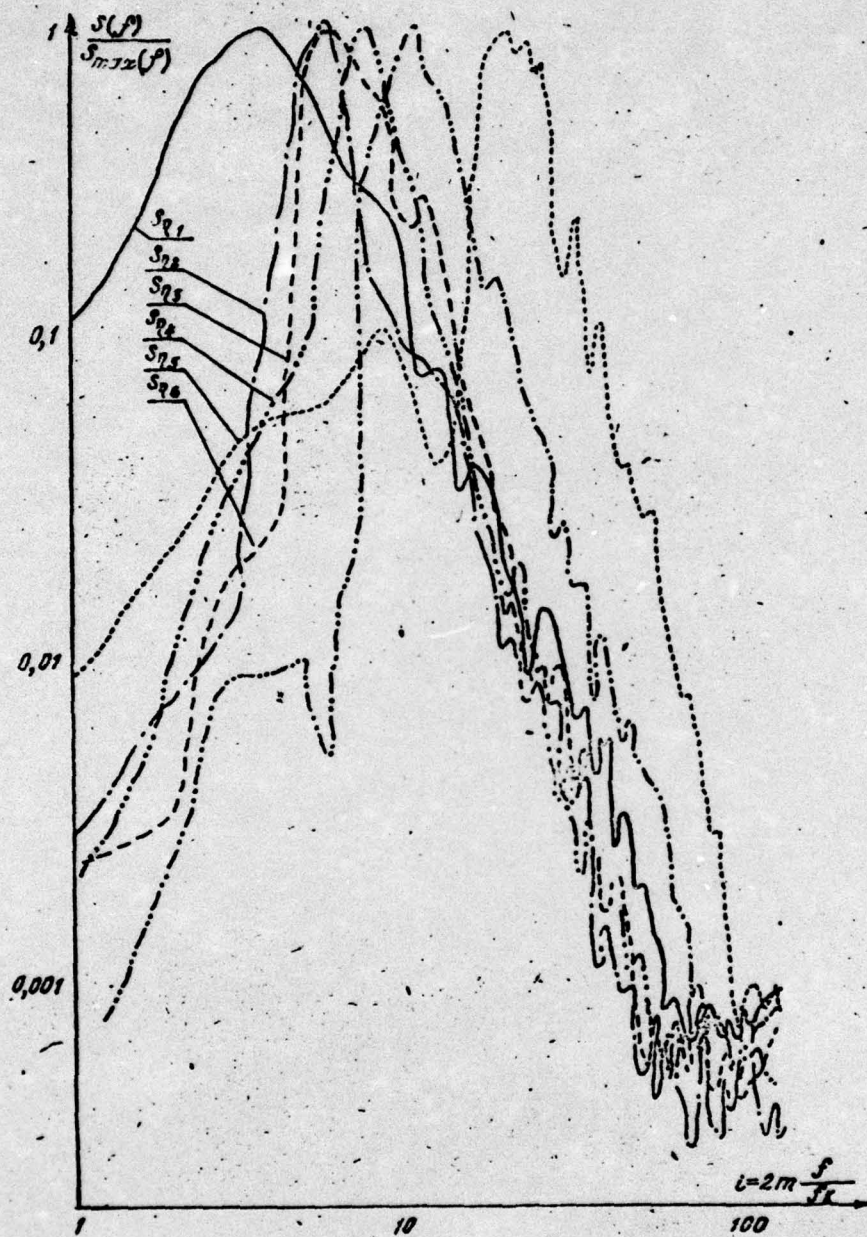


Figure 5. Spectra of sea surface elevation, obtained with an adaptive meter under various hydrometeorological conditions ($P_q = 3$).

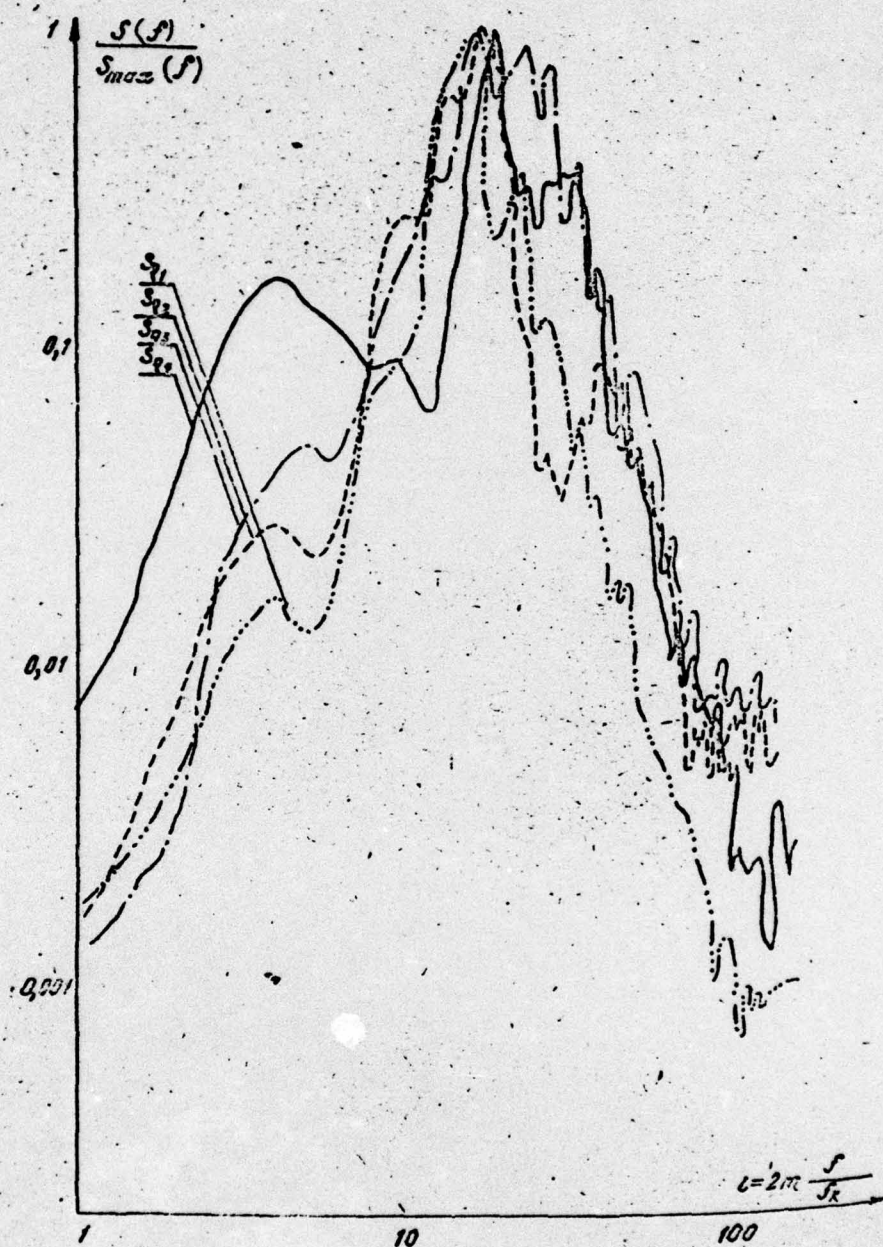


Figure 6. Spectra of sea surface elevation, obtained by the traditional nonadaptive method of measurement under various hydrometeorological conditions.

abscissa axis, and $\frac{s}{s_{\max}}$, along the ordinate axis. The graph shows that a specified spectral decrease of three orders of magnitude is provided by the meter. The measurement frequency, whose magnitude was established by the adaptive meter in each specific case, changed appreciably, as is evident from the figure. A developed wind wave at a wind speed of 7.5-8.5 m/sec and $P_q = 3$ is associated with a measurement frequency of 9-10 Hz; calm weather with a wind speed of 1.0-2.0 m/sec and $P_q = 3$ is associated with a frequency of 1.5-2 Hz.

Simultaneously with adaptive measurements, traditional measurements were also /105 performed, in which the observation frequency was 4 Hz regardless of the structure of the process studied. The results of these measurements (Fig. 6) show that the relative distortion level may vary by a factor of 10 under different conditions.

Adaptive methods with a changing measurement frequency make it possible to /106 keep constant the smallest investigated scale of the process in unsteady changes of its structure. This fact becomes particularly important in the study of the /107 statistical properties of ocean fields with well-defined unsteady properties such as intermittent turbulence, irregularity of the intensity of turbulent pulsations with depth in a stratified ocean, etc.

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